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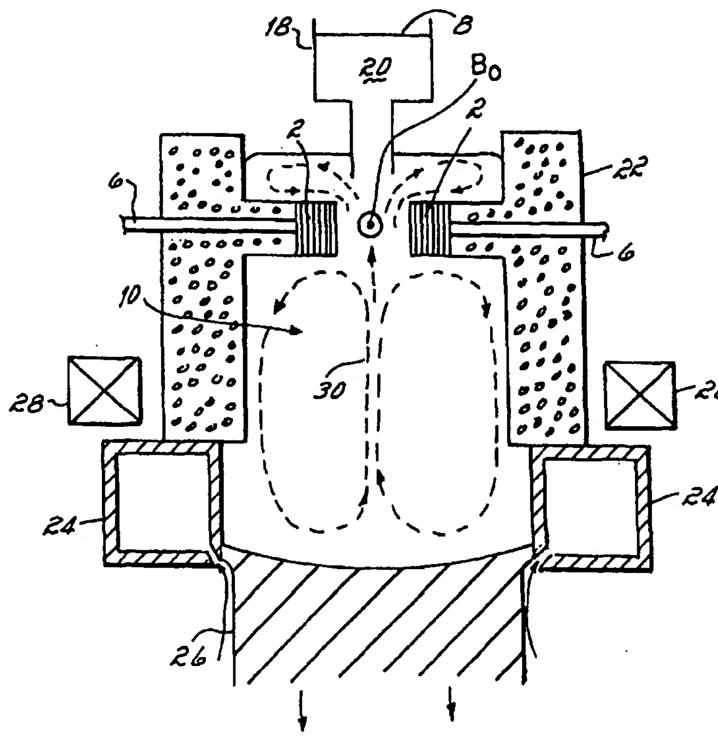
(54) Title: PROCESS FOR REFINING THE MICROSTRUCTURE OF METALS

(57) Abstract

The invention relates to a process for refining the microstructure of metals and alloys cast by the "Hot Top" technique by inducing cavitation through electromagnetic or mechanical vibration within a magnetohydrodynamic or Helmholtz resonator in combination with gentle stirring of the molten metal. For carrying out this method, a device is used having an input hopper (18) for the molten metal (20), an upper ceramic ingot mold (22) for containing the molten metal (20), a water tank (24) for water cooling the solidifying metal, a means for agitating the molten metal (20), such as an alternating electro-magnetic pump (2), a resonant cavity (10) in which to induce the cavitation phenomenon, a fixed magnetic field B_0, and an inductor coil (28) for producing a gentle stirring along flow path (30).



PROCESS FOR REFINING THE MICROSTRUCTURE OF METALS

The present invention relates to the use of cavitation effects, produced by vibrations of electro-magnetic origin during charge casting according to the so-called "Hot Top" technique, with the aim of refining to a very significant degree the microstructure of metals and alloys.

In the "Hot Top" process, a depth of liquid metal is thermally isolated and maintained in a ceramic reservoir situated above the ingot mold properly speaking, which includes a water tank. This device eliminates problems of supply and maintenance of the level of the liquid, which appear in conventional ingot molds. Moreover, surface defects, the segregations of the cortical and internal zones, as well as the distance between the branches of the dendrites are considerably reduced.

It is particularly important to obtain an effective refinement of the grain size. A fine grain is not only at the origin of a better mechanical resistance of the molded piece, but it also favorably influences the behavior of the metal during solidification (filling ability, hot cracking, major and minor segregation, etc...). The current tendency consists of adding small quantities of refining materials (magnesium, titanium, boron, for example); this method often leads to a heterogeneity of the grain structure and, as a consequence, to a deterioration of the mechanical and electrical qualities of the finished products.

During the last two decades, and particularly because of their impact on industrial casting processes, studies relating to the solidification of metallic alloys in the presence of free convection, or during the application to the bath in the process of solidification of various dynamic processing techniques causing forced convection, have become increasingly of interest.

A large number of examples can be found in the literature of cases where forces of external origin are applied in order to cause flows during the solidification of the metal, so as to reduce the size of the grains. These methods principally include rotation of the mold and mechanical or electro-mechanical stirring of the bath, as well as rheocasting. Under these conditions, the columnar-dendritic microstructure of traditionally cast pieces becomes equiaxial-dendritic, or globular, when solidified in the present of sufficiently strong forced convection which, in general, encourages the elimination of excess heat and renders uniform the temperature of the bath.

Furthermore, it has been established that the application of sonic or ultrasonic vibrations of mechanical origin during the solidification of metals and alloys modifies the macro and micro structures obtained by the traditional methods. The most commonly observed effects are the suppression of undesirable columnar and dendritic zones, and the development of a fine equiaxial structure.

Sonic or ultrasonic irradiation of melted metals is achieved mainly by using magnetostrictive or piezoelectric exciters. Shafts of quartz, graphite or ceramics connected to the exciter are used to communicate the vibrations to the heart of the molten metal. The effect of refinement of the solidification grain is caused by the hydrodynamic effects, due to turbulent oscillatory movements of the molten metal bath induced by the vibrating shaft. However, this method has several disadvantages. The oscillating shafts are very rapidly dissolved when they are submerged in the aluminum alloys, provoking an undesirable contamination of the materials. Moreover, the intensity of the vibratory phenomena rapidly decreases as the distance from the exciter increases, resulting in the refining zone being located only in the immediate neighborhood of the vibrator, and the grain size not being spread in a homogeneous manner in the cross section of the ingot. Thus, the adoption of such a system is only justified for the processing of metallic mixtures of low volume. Furthermore, because of the inherent cost and bulkiness of this equipment, the production of large ingots in continuous casting of aluminum alloys, for example, appears unrealistic. Consequently, the transmission of sonic or ultrasonic vibrations to a molten metal bath in the

process of solidification is not an easy task, which limits to a great extent the potential for application thereof in order to improve the microstructure of cast materials.

The present invention seeks to eliminate the above-described disadvantages and to refine in a homogeneous manner the solidification grain of cast pieces without adding refining materials by producing, by a resonant effect, electro-magnetic or mechanical vibrations of sufficient amplitude to lead to a cavitation phenomenon without contact either with the cast metal or with the walls of the ingot mold. This cavitation phenomenon is combined with a gentle electro-magnetic stirring, generated by an induction coil whose role is to favor the movement of crystal seeds in suspension, in such a way as to obtain a microstructure of uniform granularity throughout the volume of the ingot.

Cavitation is a term used to describe the formation of bubbles or cavities in a liquid. These cavities can be filled with air or vapor, or can be almost empty; they can be produced in liquids by the passage of sound or ultrasound waves, provided that their frequency and their intensity is appropriate. Because of oscillations of the medium, compressed and rarified regions are formed. In the rarified regions, a "negative pressure" (tension) can exist, and air or vapor bubbles then appear. In most liquid metals, a non-negligible quantity of gas is present in the form of very small bubbles, which most often are seeded from pre-existing pockets of gas. The liquid can also evaporate in the partial vacuum produced by the sudden expansion of non-dissolved gas bubbles. The efficiency of the cavitation in processes such as the purification, dispersion and refinement

of the solidification grain, is due in a major part to the very high pressures produced locally during the implosion of cavities. During this implosion period, the walls of the bubble shrink until they collide with the little seeds of gas or vapor contained in the cavity, which at that moment is extremely compressed. It has been shown that the pressure in the bubbles immediately before their final implosion can reach several tens of thousands of atmospheres. Thus, when the bubbles disintegrate, extremely powerful shock waves appear that are responsible for most of the phenomena observed under cavitation conditions. In particular, during the solidification of metals and alloys, the forces brought into play by the cavitation cause the dislocation of crystals in the course of their growth. This disintegration of the crystals produces a very large number of seeds around which new crystals grow, and as a result, these crystals cannot grow beyond a certain size.

The appearance of cavitation in the liquid metal depends upon the percentage of the most volatile undissolved gas in the liquid. It has been established that, in the case of aluminum alloys, the hydrogen content controls the appearance of the phenomenon. The solubility of hydrogen in aluminum depends on the partial pressure of the gas and on the temperature of the bath. At a constant temperature, the equilibrium concentration of gas in solution is proportional to the square root of the partial pressure. As an example, for a bath temperature of 650°C, the hydrogen content is of the order of 0.3 p.p.m., and the corresponding equilibrium pressure is 0.29 Bar.

Cavitation arises with greatest efficiency during the negative pressure of one period or of a series of periods, and this results in nucleations caused either by the modification of the equilibrium temperature, or by the cooling of the bubbles' surfaces by evaporation during their growth. In these conditions, the cavitation can appear at several positions in the liquid and at the walls of the mold, at a rate of 50 times per second. In the case of aluminum alloys, the peak of the negative pressure must be at least equal to the difference between the atmospheric pressure and the equilibrium pressure of hydrogen, that is to say of the order of 0.8 Bar. For metals other than aluminum alloys, the precise value of the amplitude of pressure variation depends on a number of factors, but in general, a pressure variation oscillating from +1 Bar to -1 Bar will cause cavitation.

The method of the present invention wherein electro-magnetic vibrations are produced consists of simultaneously applying, in a "marsh" region of the ingot being cast by the "Hot Top" process, a constant magnetic field B_o and a sinusoidal electric current of frequency N and of maximum intensity I_o ($I_t=I_o \sin \omega t$), which are horizontal and perpendicular to one another.

These conditions are achieved under conditions of forced vibration by an alternating electro-magnetic conduction pump, forming a rectangular cavity of width 1, length L and height h, containing the molten metal. An electro-magnetic force $F=B_oI_oL \sin \omega t$ appears which creates a vibratory electro-magnetic pressure $P=B_oI_o/a \sin \omega t$, whose amplitude $P_o=B_oI_o/a$ must be of the order of a Bar (10^5 Pascals) in order to efficiently cause the cavitation phenomena. As an example,

for a distance of around 10 cm, this value is reached by B_o=1 Tesla and I_o= 10,000 Amperes. In order to avoid the injection of a current of such a high intensity, a technique has been adopted which consists of continuously adjusting the frequency of the electro-magnetic vibrations, so as to achieve a state of resonance in the bath. Once resonance is observed at a particular frequency, the frequency is fixed so as to maintain the state of resonance. The relationship $P_o=B_oI_o/2$ still holds approximately true for different shaped cavities, provided that the dimensions of the cavity (e.g., height and diameter) do not differ from one another by an order of magnitude or more.

Under these conditions, the intensity of the magnetic field and the electric current are significantly reduced. The cost of the installation and the expended energy are also significantly limited. This result is attained by means of the extension of the principal of the Helmholtz (resonant cavity) resonator to magnetohydrodynamics.

The Helmholtz resonator consists of a cavity almost completely enclosing a volume of air, with a little neck or orifice that constitutes a coupling between the air in the bottle and that of the room. The shape of the cavity is not important. It can be spherical or cylindrical, as long as its smallest dimension is greater than that of the neck. Moreover, the dimensions of the resonator are small in comparison to the wavelength of resonance.

The principle of the magnetohydrodynamic (MHD) resonator is very close to that of a Helmholtz resonator. This new resonator consists of a cavity

containing a liquid metal, and whose neck is surmounted by an alternating electro-magnetic conduction pump, similar to that already described.

This pump plays the role of an exciter for the resonant cavity. An alternating voltage of frequency N is applied between the two electrodes, while a constant (or stationary) magnetic field B_o is applied perpendicularly to the varying electric current.

The behavior of this MHD resonator has first been studied using a laboratory model. The internal dimensions of the electro-magnetic pump were: width a = 30 mm, length L = 100 mm, height h = 65 mm. The internal dimensions of the cylindrical resonant cavity filled with molten aluminum were 150 mm for the diameter and 145 mm for the height.

The maximum value of the electro-magnetic pressure in the cavity, measured by a piezoelectric sensor, and corresponding to the resonance frequency, was detected by variations in the frequency of the electric current achieved by a frequency generator. Resonance was obtained for N = 217 Hz, and it was observed that, when all other conditions remain unchanged (i.e., the same magnetic induction field and the same electrical current intensity), the amplitude of the vibratory electro-magnetic pressure in the cavity was increased by a factor P* of the order of 40, in comparison to the pressure created by an alternating voltage of 50 Hz. As an example, an alternating pressure whose maximum amplitude was 1 Bar was obtained for B_o = 0.25 Teslas and I_o = 1000 Amperes, which are values that are easy to attain.

An alternative method of the present invention involves vibrations caused mechanically by a vibrating shaft connected to an exciter, animated by any type of periodic movement, and which can emit rectangular signals or saw tooth signals, for example, and preferably sinusoidal signals. The exciters can be magnetostrictive, piezoelectric or electro-magnetic, and the movements which they generate are regulated in frequency and amplitude by a low frequency supply (20-20,000 Hz), with incorporated amplifier and with digital display of the frequency.

The vibrating shafts are constructed from high performance materials (high point of fusion, very high resistance to wear and corrosion at high temperatures), such as zirconium or certain superalloys (CMSX-10, MC2, PWA 1484, for example).

The existence of the cavitation phenomenon depends on the creation of "negative pressures" (tensions) of the order of a Bar, which requires the bringing into play of high vibration energies which can only be created by very powerful frequency generators and exciters, which are costly and bulky. The latter disadvantage is prohibitive in practice for the case of continuous casting installations.

The technique thus adopted consists of the adjustment of the frequency of the vibrations of the shaft in such a way as to achieve a state of resonance in the molten metal bath. This result is attained by the application of the principle of the Helmholtz resonator (resonating cavity). This principle was discussed in the previous embodiment.

In the method described here, the liquid metal contained in the cavity delimited by the ingot mold plays the role of the resonator, the lower part of the neck of the ingot mold plays the role of the orifice, and the vibrating shaft that of the exciter for the resonant cavity. So as to attain the conditions necessary for a satisfactory refining of the crystalline structure of the cast ingots, a resonance frequency N* is attained, and the vibratory energy is modulated by the variation of the amplitude α of the vibrations of the shaft (the oscillatory mechanical power is proportional to α^2N^2).

It is important to note that this refining technique is specific to the "Hot Top" casting process because, in view of the shape of the ingot mold, as well as that of the solidification surface (practically horizontal), the volume occupied by the metal in the process of solidification constitutes a resonant cavity, similar to that of a Helmholtz resonator. Moreover, the base of the coaxial tube on top of the cylindrical cavity constitutes the coupling orifice between the vibrator and the cavity.

This technique could not be used in the traditional continuous casting technique with a free surface because the resonant phenomenon could not be set up without the appearance of undesirable phenomena. In fact, the traditional casting is characterized by the presence of a free surface, whose area is of the order of the cross section of the ingot; moreover, the shape of the solidification surface is substantially conical, which leads to a resonance which is not sharp. The introduction of a high vibratory energy at the heart of the "marsh" region

would thus cause the apparition of a very violent and disordered agitation of the molten metal, as well as a severe instability of the free surface.

The embodiments of the present invention were further improved by the addition of a single or multi-turn inductor coil fed with a sinusoidal electric current of frequency N', such that the coil surrounds the ingot mold. The coil may be placed either just above the water tank or inside the water tank, depending on the direction of flow desired. This inductor generates in the "marsh" region a periodic axial magnetic field B_t. When a mold containing molten metal is subjected to the field B_t, induced electric currents of density J are created in a plane perpendicular to the average direction of the magnetic field and concentrate, as well as the magnetic field B_t, in the peripheral zone whose thickness is arbitrarily evaluated by the skin depth $\delta = (2/\omega'\sigma\mu)^{1/2}$, where $\omega' = 2\pi N'$ is the frequency of the electric current (or of the magnetic field), and μ and σ are, respectively, the magnetic permeability and the electric conductivity of the molten metal. This is the very well-known phenomenon known by the name of "skin effect." The induced magnetic field and electric current, both variable, interact in all these cases to create Laplace forces J x B per unit volume, whose average value during the period is non-negligible, and which possess a rotational component caused by edge effects (curvature of the lines of magnetic force at the entrance and exit of the mold), and which are responsible for a stirring movement. This phenomenon appears in crucible induction furnaces and in numerous refining processes of the microstructure of metal alloys. It has been

particularly described in French patents n° 83 01999 (inventor Charles Vivès) and n° 83 19971 (inventor Charles Vivès).

Here, a gentle stirring, of the order of some $cm \cdot s^1$, renders the temperature of the bath uniform and favors the movement of seeds while avoiding erosion of the refractory wall surfaces, which could be a cause of pollution of the metal.

The device according to the invention has numerous advantages:

— it is simple in conception and realization;

— its energy consumption is low (less than 1 $kW \cdot h^{-1}$ for large ingots);

— the intensity of the vibratory phenomena can be modulated with great flexibility, either by a) in the case of electro-magnetic vibration, variation of the amplitude of the magnetic field B_o, or variation of the intensity and/or of the frequency N of the alternating current flowing through the electro-magnetic pump; or b) in the case of mechanical vibration, variation of the amplitude α, and the vibration frequency N of the shaft;

— it enables very efficient refining of the solidification grain and homogenization of the ingot microstructure and, as a consequence, considerably improves the mechanical and electrical performance of the finished products; and

— it can be applied to all metals and alloys produced by continuous casting according to the "Hot Top" process.

Moreover, the invention will be better understood with the aid of the drawings which accompany the present application and which represent, without

limitative character, examples of embodiments of devices according to the invention.

Fig. 1 diagrammatically shows the principle of the alternating electro-magnetic pump, capable of causing the cavitation phenomena (here by forced vibrations).

Fig. 2 diagrammatically shows the principle of the magnetohydrodynamic resonant cavity, capable of provoking the cavitation phenomena (here by vibrations at the resonance frequency).

Fig. 3 shows a cross section of the grain refining device, associated with "Hot Top" casting, characterized by the use of an electro-magnetic conduction pump for producing vibration and by the positioning of the inductor coil above the water tank.

Fig. 4 shows a cross section of the grain refining device, associated with "Hot Top" casting, characterized by the use of an electro-magnetic conduction pump for producing vibration and by the positioning of the inductor coil within the water tank.

Fig. 5 represents a cross section of the grain refining device, associated with a "Hot Top" casting, characterized by the use of a vibrating shaft for producing vibration and by the positioning of the induction coil above the water tank.

Fig. 6 represents a cross section of the grain refining device, associated with the "Hot Top" casting, characterized by the positioning of the inductor coil within the water tank.

Fig. 7 is a micro-image of molten metal with the conventional columnar-dendritic microstructure.

Fig. 8 is a micro-image of molten metal refined by vibration, but at an electro-magnetic pressure insufficient to induce cavitation.

Fig. 9 is a micro-image of a molten metal refined by the method of the present invention.

In Fig. 1, there is shown an alternating electro-magnetic pump 2 having electrodes 4 and input connections 6 for the alternating current. There is also shown the free surface of the liquid metal 8, the constant magnetic field B_o, and the vibratory electro-magnetic pressure P_t, as well as the periodic parameters of electric current density J_t, electro-magnetic force F_t, and speed of the liquid metal U_t.

In Fig. 2, there can be seen the free surface of the liquid metal 8, the resonant cavity containing the molten metal 10, the alternating electro-magnetic pump 2 with input connections 6, the fixed magnetic field B_o and a pressure sensor 12.

Figs. 3 and 4 show, in cross section, two examples of devices associated with the "Hot Top" process in which vibrations of electro-magnetic origin are produced and relating to two variants concerning the positioning of the inductor coil. There can be seen the input hopper 18 for the molten metal 20, having a free surface 8, an upper ceramic ingot mold 22 for containing the molten metal 20, a water tank 24 for water cooling the solidifying metal, the alternating electro-magnetic pump 2 with input connections 6 for agitating the molten metal

20, the resonant cavity 10 in which to induce the cavitation phenomenon, the fixed magnetic field B_o, the solidified portion of the ingot 26, and the inductor coil 28 and 28', respectively, which produces the flow path 30 of the molten metal 20.

Figs. 5 and 6 show, in cross section, two examples of devices associated with the "Hot Top" process in which vibrations of mechanical origin are produced and relating to two variants concerning the positioning of the inductor coil. There can be seen the input hopper 18 for the molten metal 20 having a free surface 8, an upper ceramic ingot mold 22 for containing the molten metal 20, a water tank 24 for water cooling the solidifying metal, the exciter 36 and vibrating shaft 38 for agitating the molten metal 20, the resonant cavity 10 in which to induce the cavitation phenomenon, the solidified part of the ingot 26, and the inductor coil 28 and 28', respectively, which produces the flow path 30 of the molten metal 20.

The invention can be illustrated with the help of the following example.

An aluminum alloy (A 356) contained in an ingot mold of 150 mm in diameter was subjected to alternating electro-magnetic pressures of increasing amplitude produced by the pump in the resonant cavity while the inductor coil was excited by a constant magnetic force, in all the tests, of 1000 Ampere-turns. After irradiation (one minute for two kg of solidified liquid metal), samples were taken, polished, and chemically attacked, so as to reveal their microstructures.

Fig. 7 shows the micro-image of a non-irradiated sample, characterized by a conventional columnar-dendritic microstructure.

Fig. 8 corresponds to peaks of electro-magnetic pressure close to 0.5 Bar, insufficient to obtain the phenomenon of cavitation, but capable of imposing levels of viscous shear appropriate to homogenize the temperature of the "marsh" and favorize seeding. This multiplication of the seeds is seen by a refinement of the solidification grain characterized by the presence of globular crystals, whose average diameter is around 150 microns.

Fig. 9 corresponds to peaks of alternating electro-magnetic pressure of 1.16 Bar, imposed 192 times per second. The observation of this microstructure, obtained in conditions where cavitation exists, shows that the grains are finer (30 microns in average diameter) and less globular than those produced in the absence of cavitation (Fig. 8). Moreover, the disappearance of agglomerates can be noted. In comparison with Fig. 9, the number of grains is multiplied approximately by 500, which shows the superiority of the solidification grain refinement technique using cavitation in a resonant cavity, in comparison with dynamic techniques based on forced convection.

The behavior of this process was also studied in a cylindrical resonant cavity, filled by a molten aluminum alloy (A 356), whose dimensions were 150 mm in diameter and 145 mm in height. This cavity was surmounted by a coaxial tube of 60 mm in diameter and 70 mm in height whose lower portion played the role of the coupling orifice. A steel shaft of 20 mm in diameter, placed in the vertical tube of 60 mm in diameter, was excited by an electro-magnetic vibrator of regulatable frequency and amplitude. The vibrator emitted vibrations of 7 mm in amplitude and of increasing frequency starting at 20 Hz. The tests showed

that the resonant frequency was reached in the molten metal for N* = 270 Hz. It was observed that the amplitude of the vibratory electro-magnetic pressure in the cavity was increased by a factor P* of the order of 20, in comparison with the pressures attained at frequencies less than 265 Hz or greater than 275 Hz. After irradiation (one minute for two kg of solidified liquid metal), samples were taken, polished and chemically attacked, so as to reveal their microstructures.

Under conditions where the cavitation phenomenon existed, the columnar-dendritic structure, characteristic of conventional "Hot Top" casting, was replaced by a microstructure which was very fine and equiaxial (average diameter of 30 microns) and homogeneous throughout the ingot, such as that shown in Fig. 9. Moreover, the highly segregated cortical zone had practically disappeared.

Finally, both tests showed that the directions of the convective flows were inversed when the inductor coil was placed within the water tank, as shown in Figs. 4 and 6. In this case, the flow descends in the central zone of the "marsh", which is preferable because it avoids the risk that the oxide layer, which generally covers the free surface, will be drawn into the interior of the ingot, thus avoiding any pollution of the metal.

The invention can be applied in all cases where it is desireable to obtain a very fine and homogeneous microstructure, with the aim of improving the mechanical and electrical performance of metals and alloys produced by the so-called "Hot Top" charge casting technique.

WHAT IS CLAIMED IS:

1. A process for solidifying molten metals and alloys continuously cast by the Hot Top technique into an ingot mold, comprising the steps of:

producing an electro-magnetic field by a current of frequency N;

applying the electro-magnetic field in a resonant cavity, and

producing resonance in the molten metal or alloy in the resonant cavity.

2. The process of claim 1, wherein the electro-magnetic field is created by an electro-magnetic conduction pump, through which the current of frequency N is flowing.

3. The process of claim 1, wherein the electro-magnetic field is an alternating electro-magnetic field produced by an alternating current of frequency N.

4. The process of claim 1, wherein the resonance is obtained by adjusting the frequency N.

5. The process of claim 1, wherein the frequency N is about 1 to 10,000 Hertz.

6. The process of claim 1, further comprising placing an inductor coil supplied with an electric current of frequency N around the ingot mold, so as to obtain a forced convection of low intensity.

7. The process of claim 6, wherein the inductor coil is a single-turn inductor coil supplied with a monophase sinusoidal electric current of frequency N.

8. The process of claim 6, wherein the inductor coil is a multi-turn inductor coil supplied with a monophase sinusoidal electric current of frequency N.

9. The process of claim 6, wherein the ingot mold includes a water tank above which the inductor coil is placed.

10. The process of claim 6, wherein the ingot mold includes a water tank within which the inductor coil is placed.

11. A process for solidifying molten metals and alloys continuously cast by the Hot Top technique into an ingot mold, comprising the steps of:

producing an electro-magnetic field by an electro-magnetic conduction pump through which a current of frequency N is flowing;

applying the electro-magnetic field in a resonant cavity containing the molten metal or alloy so as to produce cavitation within the resonant cavity;

producing resonance in the molten metal or alloy in the resonant cavity; and

placing an inductor coil supplied with an electric current of frequency N around the ingot mold, so as to obtain a forced convection of low intensity.

12. The process of claim 11, wherein the inductor coil is a single-turn inductor coil supplied with a monophase sinusoidal electric current of frequency N.

13. The process of claim 11, wherein the inductor coil is a multi-turn inductor coil supplied with a monophase sinusoidal electric current of frequency N.

14. The process of claim 11, wherein the ingot mold includes a water tank above which the inductor coil is placed.

15. The process of claim 11, wherein the ingot mold includes a water tank within which the inductor coil is placed.

16. A process for solidifying molten metals and alloys continuously cast by the Hot Top technique into an ingot mold, comprising the steps of:

imposing vibrations of mechanical origin within a resonant cavity, said resonant cavity containing the molten metal or alloy, so as to produce cavitation

within the resonant cavity, wherein the vibrations are generated by a vibratory movement of frequency N;

producing resonance in the molten metal or alloy in the resonant cavity; and

placing an inductor coil supplied with an electric current of frequency N around the ingot mold, so as to obtain a forced convection of low intensity.

17. The process of claim 16, wherein the vibrations are generated by a shaft animated by a sinusoidal movement of frequency N.

18. The process of claim 16, wherein the resonance is obtained by adjusting the frequency N.

19. The process of claim 16, wherein the inductor coil is a single-turn inductor coil supplied with a monophase sinusoidal electric current of frequency N.

20. The process of claim 16, wherein the inductor coil is a multi-turn inductor coil supplied with a monophase sinusoidal electric current of frequency N.

21. The process of claim 16, wherein the ingot mold includes a water tank above which the inductor coil is placed.

22. The process of claim 16, wherein the ingot mold includes a water tank within which the inductor coil is placed.

23. A process for solidifying molten metals and alloys continuously cast by the Hot Top technique into an ingot mold, comprising the steps of:

inducing cavitation within a resonant cavity containing the molten metal or alloy, wherein the resonant cavity is a Helmholtz-like resonator; and

producing resonance in the molten metal or alloy in the resonant cavity.

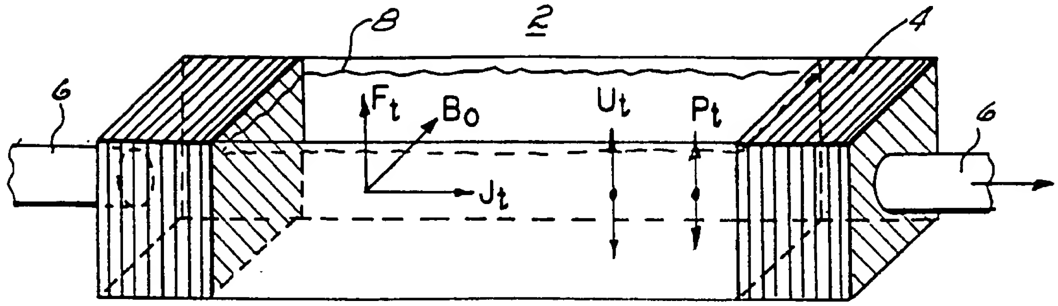


FIG.1

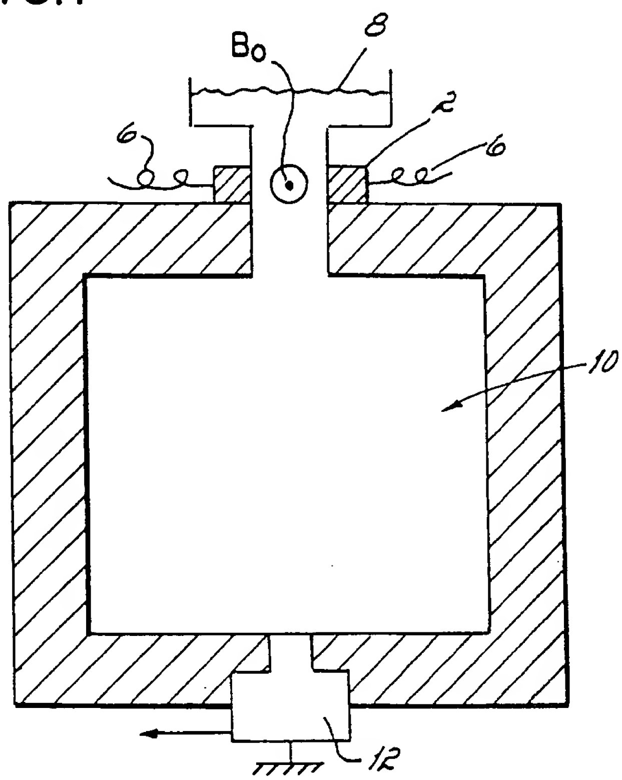


FIG.2

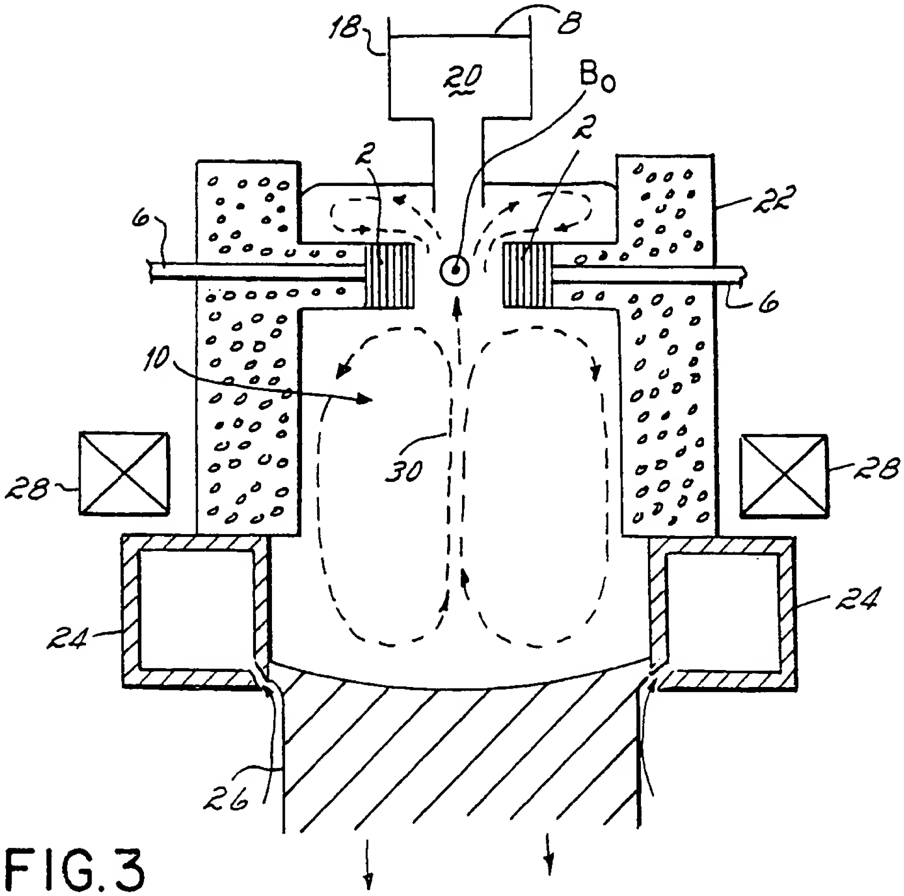

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FIG.3

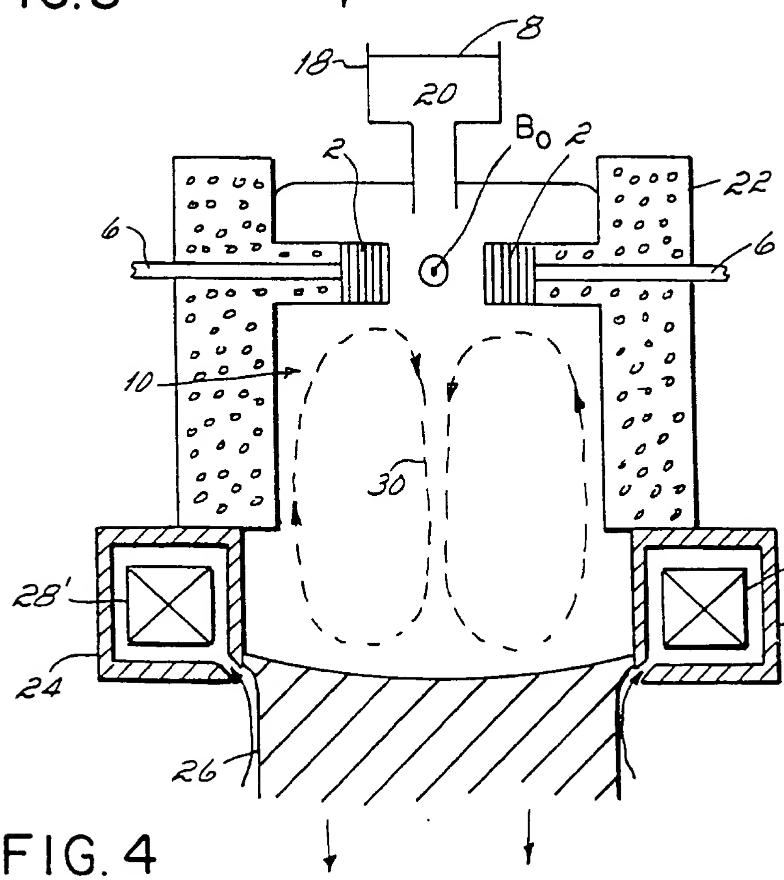
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FIG. 4

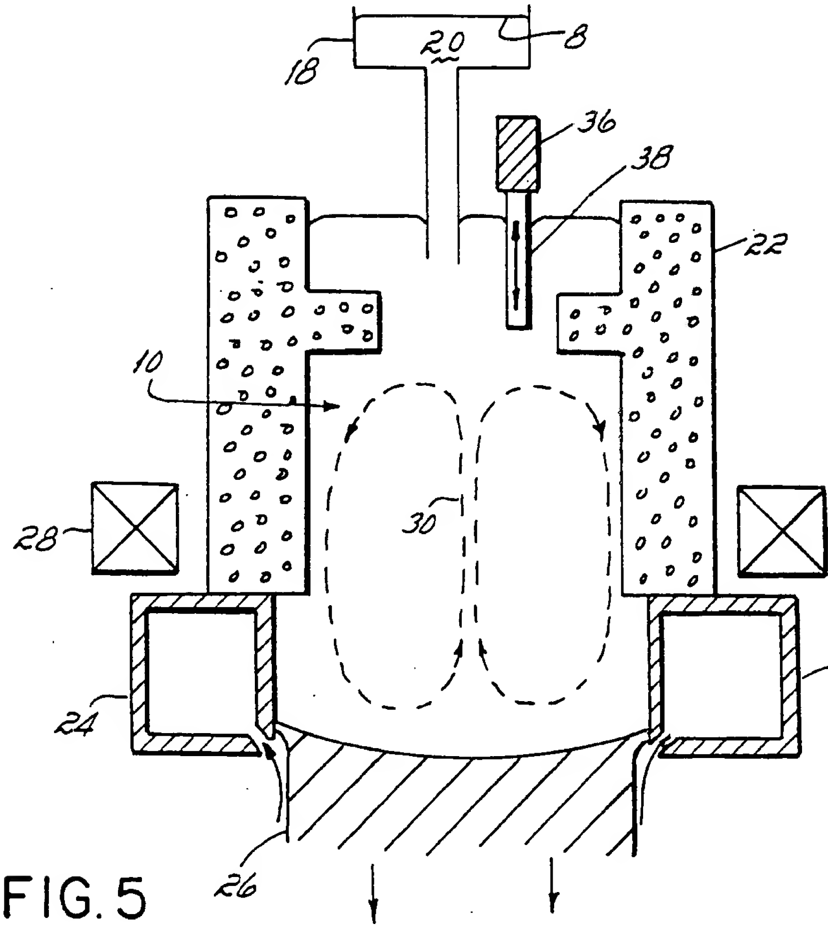
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FIG. 5

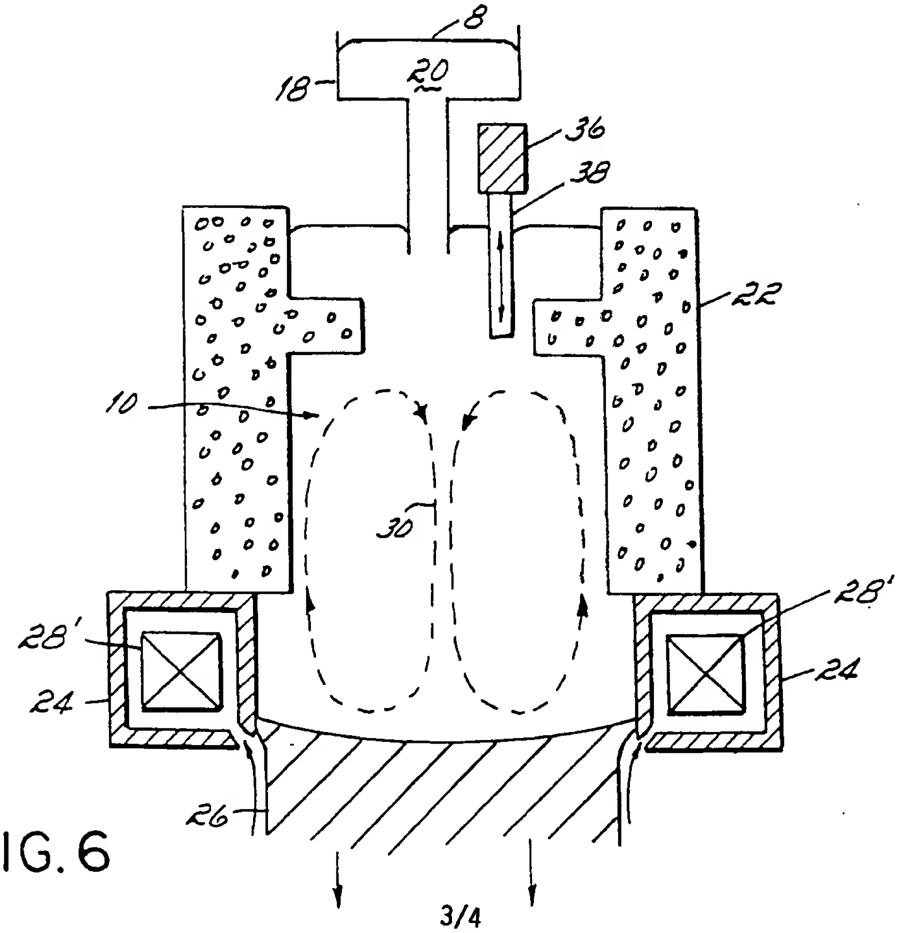
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FIG. 6

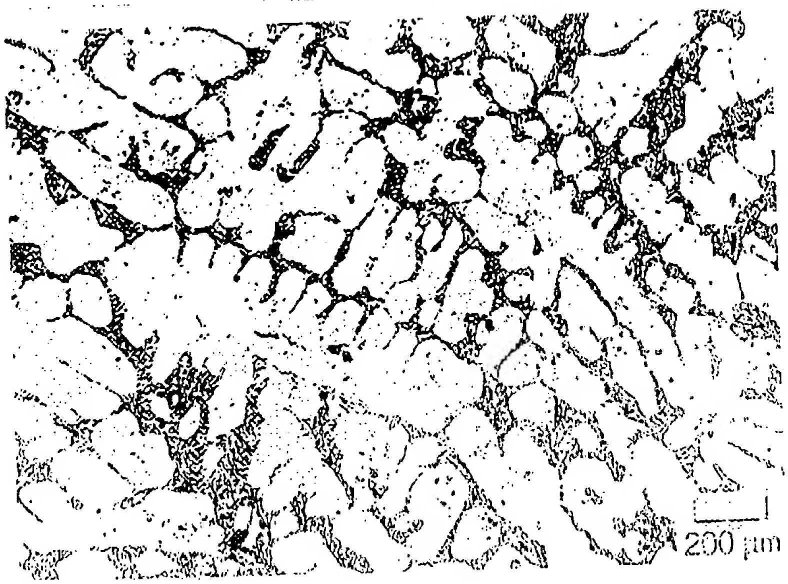

FIG.7

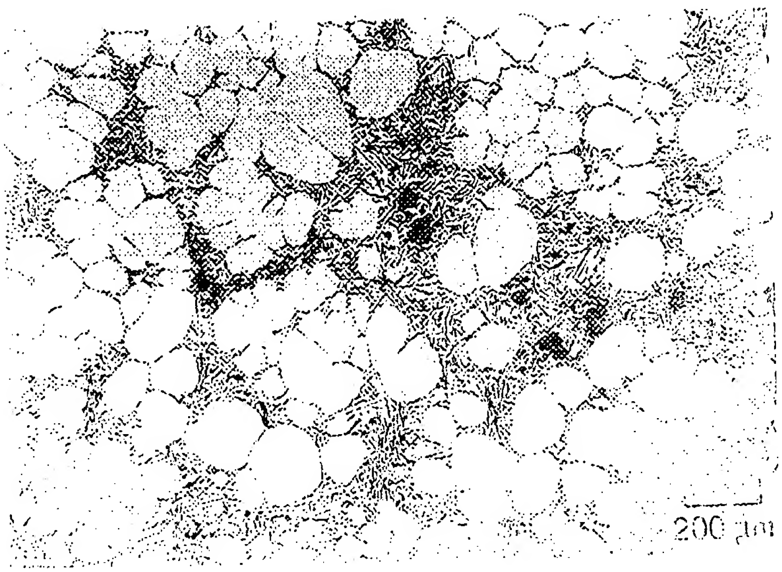

FIG.8

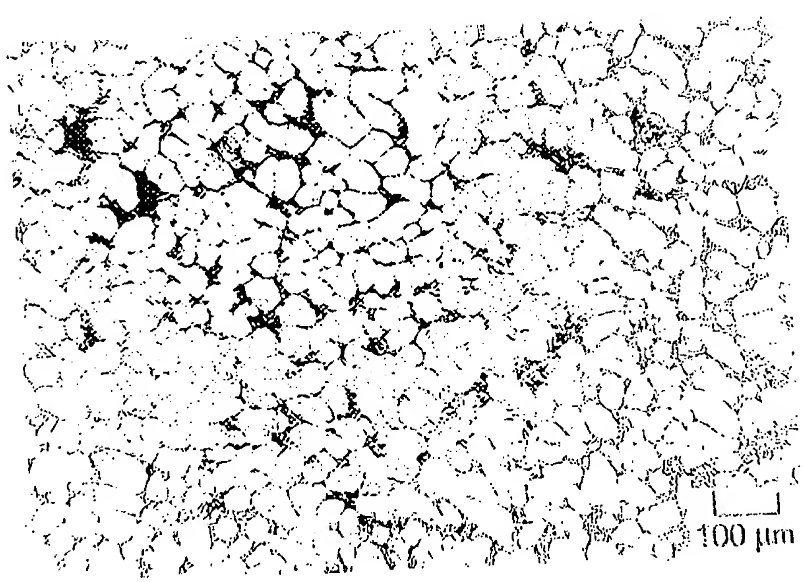

FIG.9

INTERNATIONAL SEARCH REPORT

International application No.
PCT/US98/00300

A. CLASSIFICATION OF SUBJECT MATTER

IPC(6) :B22D 11/04, 11/10, 27/02, 27/08
US CL :164/71.1, 147.1, 416, 466, 478, 487, 502, 900
According to International Patent Classification (IPC) or to both national classification and IPC

B. FIELDS SEARCHED

Minimum documentation searched (classification system followed by classification symbols)

U.S. : 164/71.1, 147.1, 416, 466, 478, 487, 502, 900

Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched

Electronic data base consulted during the international search (name of data base and, where practicable, search terms used)

APS

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
Y	JP 57-75,269 A, (Nippon Kokan KK) 11 May 1982, Abstract, and figures 1 and 2.	1-23
Y	JP 59-199,147 A (Kouji Kawamura) 12 November 1984, Abstract, and figures 4 and 5.	1-15, 23
Y	FR 2,628,994 A (Charles Vives) 29 September 1989, Abstract, figure 3.	14, 21
Y	US 4,373,950 A (Shingu et al) 15 February 1983, col. 3, lines 28-65, and figure 1.	16-22
Y	US 5,186,236 A (Gabathuler et al) 16 February 1993, col. 3, line 40 through col. 5, line 2.	16-22

☐ Further documents are listed in the continuation of Box C. ☐ See patent family annex.

* Special categories of cited documents:

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"P" document published prior to the international filing date but later than the priority date claimed

"T" later document published after the international filing date or priority date and not in conflict with the application but cited to understand the principle or theory underlying the invention

"X" document of particular relevance; the claimed invention cannot be considered novel or cannot be considered to involve an inventive step when the document is taken alone

"Y" document of particular relevance; the claimed invention cannot be considered to involve an inventive step when the document is combined with one or more other such documents, such combination being obvious to a person skilled in the art

"&" document member of the same patent family

Date of the actual completion of the international search	Date of mailing of the international search report
02 APRIL 1998	14 MAY 1998

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